General Effects of Fractionation, Assimilation, and Mixing on Trace Element Evolution

A Senior Honors Thesis

Presented in Partial Fulfillment of the Requirements for graduation **with distinction in Geology and Mineralogy** in the undergraduate colleges of The Ohio State University

by

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The Ohio State University
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Project Adviser: Professor Michael Barton, Department of Geological Sciences

Senior Thesis

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Approved by:

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Dr. Michael Barton

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Abstract

In recent years, geochemists have become increasingly interested in describing the processes that effect the chemistry of evolving magmas. As research in this field has progressed, it has become apparent that fractional crystallization cannot account for all the geochemical variations present in lavas. Increasingly, geologists have begun to look at other processes, such as assimilation and magma mixing, to explain the development of a variety of lavas. However, no one has attempted to describe the effects that these processes might have in combination. This thesis is an attempt to describe the general effects that combined fractionation, assimilation and mixing might have on an evolving magma body.

Detailed models simulating the processes of combined fractionation, assimilation, and mixing were developed using the modified equations of O'Hara and Mathews (1981). These models were used in analysing data obtained from Patmos Dodecanesos, Greece. Patmos, a volcanic island in the south eastern Agean Sea, is composed of alkaline volcanics. Previous studies by Wyers and Barton (1986, 1987) indicate that assimilation and mixing have affected the chemistry of Patmos, making the geochemical data obtained from Patmos ideal for modeling.

The development of apparent isochrons in recent lavas using combined AFC and mixing models illustrates the importance of understanding these processes and their effects on magma chemistry.

Further, models developed during this research reveal that magma mixing greatly complicates the analyses of volcanic rocks generating predominately non-linear trace element trends.

LIST OF FIGURES

Introduction and Purpose

This study was begun in an attempt to quantitatively model the geochemical changes that occurred in the magma chamber beneath Patmos, Dodecanesos Greece. Patmos is composed of alkaline volcanics ranging in age from four to seven million years.

Earlier studies by Wyers and Barton (1986,1987) indicate that magma mixing and assimilation, along with fractional crystallization, played an important role in the evolution of the Patmos lavas. Mass balancing calculations indicate that the chemistry of the hy-trachybasalts cannot be explained by simple fractional crystallization of parental ne-trachybasalts. Complex zoning and resorption of phenocrysts indicate that the lavas are hybrids formed by mixing of ne-trachybasalts and hy-trachyandesites (Wyers and Barton, 1986). Mixing proportions are estimated, by Wyers and Barton (1986), to be approximately 77 to 80% ne-trachybasalt and 23 to 20% trachyandesite, and it is estimated that mixing preceded the eruption by 12 hours to 2 weeks, thereby indicating that eruption was triggered by a mixing event. However, combined fractionation and mixing do not sufficiently explain the low MgO concentrations or the high P_2O_5 concentrations in the hy-trachybasalts. It is believed, therefore, that this is an indication of assimilation.

As this study has progressed, its scope has changed to a more general analysis of the affects that combined fractionation, assimilation, and magma mixing might have on an active magma chamber. Patmos remains an integral part of this thesis as all the primary data used in this study were taken from analyses of the Patmos lavas.

The modeling proposed in this thesis is applicable to future research of volcanic processes. Gross misinterpretation and error in analyses of volcanic suites can occur if the combined affects of fractionation, assimilation, and magma mixing on magma chemistry are ignored. This thesis is an attempt to:

A.) quantitatively demonstrate the influence of assimilation, mixing, and fractionation on a hypothetical magma chamber.

B.) compare the affects of:

1.) fractionation, assimilation, and mixing

2.) fractionation and assimilation

3.) fractionation

General geology

The volcanic island of Patmos is located in the Southeastern Aegean Sea and lies approximately 100 km north of the Hellenic Arc. Figure 1 is a location map of the Agean. The dashed line to the south represents the subduction trench, the dashed line to the north represents the Hellenic arc, and volcanics are mapped in black. Patmos encompasses an area of some 38 Km^2 and is composed of alkaline to sub-alkaline volcanics (Barton and Wyers 1986, 1987).

Volcanism along the Hellenic arc is calc-alkaline in nature, and is most likely the result of a continent to continent collision involving subduction of the African plate under the

Aegean microplate (Wyers and Barton, 1987). Subduction along the plate is approximately perpendicular to the axis of the Hellenic trench (Huijsmans, 1985) and has been estimated at a rate of 5-7 cm/yr (Angelier et al., 1982). Subduction along the trench was initiated approximately 13 m.y.a.

Robert (1973) described the geology and petrology of Patmos. According to her, the central part of Patmos lies in a NW-SE trending graben, and the major volcanic suites on the island include: high-K and Al basalts, intermediate potassic lavas (latite, quartz-latite, and potassic trachytes), quartz-potassic alkaline lavas (quartz-trachytes and phonolites), sodic-alkaline lavas (trachytes and phonolites), and pyroclastics (fig.2).

Wyers and Barton (1987) believe at least three main volcanic events occurred on Patmos, taking place approximately 4 and 7 million years ago. The last major eruption along the Hellenic arc took place on Santorini in 1950.

Methodology

Three basic computer models were developed for this thesis (see appendices a, b, and c).

The first program was developed using modified equations by O'Hara and Mathews (1981). This program requires as input: x (the amount of crystallization), y (the amount of material erupted), w (the amount of material assimilated), z (the amount of material replenished), the initial concentration of the trace element (or isotope ratio) of the system of interest in the parent magma, the assimilant, and the recharge magma. Also, the distribution coefficient for the trace element system being modeled must be input.

For the purpose of simplicity, it was assumed that the magma chamber was being continually replenished by a hot primitive magma of constant composition. All the above parameters may be held constant or varied. Variation of each parameter independently allows its influence in the magma chamber to be analysed. For the purpose of this study, each model was taken through ten cycles. During each cycle, the magma experiences fractionation, assimilation, eruption, and replenishment (or mixing) in amounts specified by the input parameters.

BASIC EQUATIONS FOR FRACTIONATION FOLLOWED BY MIXING AND ASSIMILATION = (F/MA)

$$CI = CO*((1-X)^{(D-1)})$$

$$MN = MI*(1-X-Y) + W + Z$$

$$CN = (CI*MI*(1-X-Y))/MN + (Z*Cz)/MN + (W*Cw)/MN$$

where:

CO = Initial concentration of trace element in parent magma

CI = Concentration of trace element after fractionation

D = Distribution coefficient for trace element

MI = Initial mass in magma chamber

MN = Mass of liquid remaining at any given time

CN = Concentration of trace element at any given time

N = The number of cycles the chamber has gone through

CW = Concentration of the trace element in the assimilant

CZ = Concentration of the trace element in the recharge magma

X = The amount crystallized

Y = The amount erupted

Z = The amount of recharge

W = The amount of assimilant

The second and third major programs were designed to model the variation in chemistry of trace elements and isotopes (respectively) as a result of combined fractionation and assimilation. These equations were developed by DePaolo (1981).

BASIC EQUATIONS FOR FRACTIONATION AND ASSIMILATION

$$CM = Co*(F^{(-Z)}) + (R*CS*(1-F^{(-Z)}))/(Z*(R-1)*Co$$

R = Mass assimilated over mass crystallized (MA/MC)

Z = (R+D-1)/(R-1)

F = the amount of liquid remaining in the chamber

Co = the initial concentration of the trace element

CS = Concentration of the trace element in the assimilant

The final model developed calculates the effects of simple fractional crystallization on a magma chamber. The only equation used by this model is the Raleigh Fractionation Equation, which is defined as:

$$Ci/Co = F^{(D-1)} = (1-X)^{(D-1)}$$

where:

Ci = Concentration of element of interest after fractionation

Co = the initial concentration of the element in the magma

F = the amount of liquid remaining after fractionation

D = The distribution coefficient of the trace element

A range of compatible elements (which partition into the solid during fractionation, $D_i^{s/l} > 1$) and incompatible elements (which partition into the melt during fractionation, $D_i^{s/l} < 1$) were examined in each model. Incompatible elements modeled in this thesis include: Th, Zr, Rb, Sm, and Nd. Compatible elements include Sr and Ni. In addition to trace elements the $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ isotope systems were modeled. The initial values of all isotope ratios and trace element concentrations used in modeling are given in Table 1 (values are given in parts per million).

Table 1: Initial Trace Element and Isotope Values used in Modeling

	87Sr/86Sr	143Nd/144Nd	Sr	Nd	Rb	Sm	Th	Ni	Zr
Patmos-26	0.704593	0.512642	1588	5.3	103.0	9.4	9.00	98.0	226.0
Upper crust	0.709910	0.512320	350	26.0	110.0	4.5	10.50	20.0	240.0
Lower crust	0.709910	0.512320	425	11.0	8.0	3.3	1.95	35.0	30.0

For the sake of consistency, the assimilant was taken as upper crust (unless otherwise indicated), and the physical parameters were kept at x =.2, y = .2, z = .1, and w = .1 (all relative to 1).

Derivations for the equations used in this thesis may be obtained from M. Barton upon request.

Discussion

Perhaps the most important result to come out of this study is the development of what appear to be isochrons in relatively recent lavas (figs. 3 and 4).

The isochron method of dating is used routinely by geochemists to obtain dates for igneous rocks. This method relies upon the fact that in a given sample the rate of accumulation of a radiogenic isotope relative to a non-radiogenic isotope of the same element is dependent on the ratio of the radiogenic parent to the non-radiogenic daughter isotope (Cox, Bell, and Pankhurst, 1979). Thus, by plotting $^{87}Rb/^{86}Sr$ vs. $^{87}Sr/^{86}Sr$ or $^{147}Sm/^{144}Nd$ vs. $^{143}Nd/^{144}Nd$, the geochemist may extract an age for the rock from the slope. This age is derived from the equation (for Sr):

$$[^{87}Sr/^{86}Sr] = [^{87}Sr/^{86}Sr]_o + [^{87}Rb/^{86}Sr](e^{\lambda t} - 1)$$

solving for t this equation becomes:

$$t = 1/\lambda * \ln[((^{87}Sr/^{86}Sr) - (^{87}Sr/^{86}Sr)o/(^{87}Rb/^{86}Sr)) + 1]$$

where:

t = the time since the rock has crystallized

λ = the decay constant

o = the initial Sr ratio

The initial value of the $^{87}Sr/^{86}Sr$ ratio may be obtained by extrapolating the isochron to the y-intercept where $^{87}Rb/^{86}Sr = 0$.

The other value may be measured directly from the rock making the derivation of the time elapsed since crystallization a simple algebraic manipulation.

A problem with using this method to date rocks arises when assimilation and mixing have affected the initial ratios of the parent to daughter isotopes. Assimilation and/or mixing may alter the initial ratios thereby affecting the slope of the isochron which is used to derive the initial value of the isotope system of interest. This results in the sample appearing much older than it actually is.

This point can be illustrated using the apparent isochrons in figures 3 and 4. Using the above equations and the intercepts obtained for figures 3 and 4, the hypothetical ages for Patmos-26 were calculated. In Figure 3, the Sr-Rb isochron yielded an age of approximately 86 + or - 2 mya. In Figure 4, the Sm-Nd isochron yielded an age of approximately 43 + or - 1 mya. The large discrepancy in these ages, in addition to the fact that the actual age of Patmos is 4 mya., indicates the unreliability of the isochron dating method in lavas formed in subduction zones where assimilation and mixing are likely to alter the initial chemistry.

The apparent isochrons illustrated in figures 3 and 4 were developed using an initial lava identical to Patmos-26 and subjecting this lava to ten cycles of assimilation, fractionation, mixing, and eruption (model 1).

The correlation diagrams shown in figures 5 and 6 show a characteristic range in Sr and Nd values for rocks formed in a crustal magma chamber. Assimilation of crustal material results in an increase in incompatible elements (such as Th, Rb, and Sr) and a decrease in compatibles (such as Ni). Though normally classified as a compatible element, Sr is incompatible in the mantle. Because the crust is a melt product of the mantle, assimilation of crustal material normally results in the increase of Sr.

Figures 7, 8, and 9 illustrate the complex effects that assimilation, mixing, and fractionation might have on an evolving magma chamber. Figure 7 is particularly important as it illustrates the importance of using numerous samples in the analyses of these rocks. Had only the first four data points been used, one could mistake the trend in figure 7 for an isochron. Had only the last four data points been used the trend could have been mistaken four a negative isochron. Either of these analyses would be misleading. The trends of all these graphs probably illustrate an initial rise due to fractionation. However, as fractionation and eruption continue, less and less liquid remains in the chamber. This allows the affects of mixing and assimilation to dominate the process thereby causing a curve to develop in the data sets.

Figures 10 through 12 show the comparison of the effects of fractionation (model 3), fractionation and assimilation (model 2), and fractionation followed by mixing and assimilation (model 1). All the plots show similar trends. Figures 10.a, 11.a, and 12.a were derived from model 1 and, therefore, illustrate the effects of assimilation, fractionation, and mixing. Comparing plots 10.a to 10.b, 11.a to 11.b, and 12.a to 12.b allows us to see the influences of mixing and eruption on magma evolution.

From this comparison, it is obvious that mixing greatly complicates trace element evolution, changing it from a linear (figures 10.b, 11.b, and 12.b) to a slightly curved, and therefore non-linear relationship (figures 10.a, 11.a, and 12.a). In addition, the plots derived from model 1 show far less variation in trace element abundances. For example, Th ranges from approximately 1.05 to 1.20 in figure 10.a (model 1) and from approximately 1 to 2 in figure 10.b (models 2 and 3). Similar trends are present for the other graphs in this group.

Graphs 10.b, 11.b, and 12.b represent a comparison of the effects of AFC to fractional crystallization. As can be easily seen, both processes result in a linear trend for the trace elements, but the slopes of the trends of trace element data defined by each process differ. The trends resulting from AFC tend to show greater slopes and enrichment in the abundances of the trace elements being modeled.

Figure 12 represents an exception to this rule as assimilation results in the relative depletion of Ni. This is expected as Ni is a compatible element, which is indicated by the negative slopes in graphs 12.a and 12.b.

Conclusion

From the above discussion, it is apparent that fractionation, assimilation, and mixing can greatly affect the chemistry of an evolving magma body. Although more research is needed before we truly understand these processes, some basic trends were revealed during this project.

The generation of an isochron in recent lavas is a phenomenon which clearly illustrates the importance of further study in this area. The processes of assimilation and mixing can act to alter the initial parent to daughter isotope ratio, thereby making a recent lava appear to show an isochron trend. Knowing this, geologists can no longer attempt to extract ages from lavas which were likely to have undergone assimilation or mixing (ie. lavas originating from a crustal magma chamber) using the isochron method.

Overall, mixing tends to complicate the analyses of lavas. Trends that plot as straight lines for fractionation and assimilation become non-linear curves when mixing is involved. In addition, mixing with a hot primitive magma of constant composition has the affect of lessening the variation of trace element abundances.

Finally, it is obvious that mixing and assimilation can dramatically effect an evolving magma body and, therefore, we can not hope to understand magma evolution without first understanding these processes.

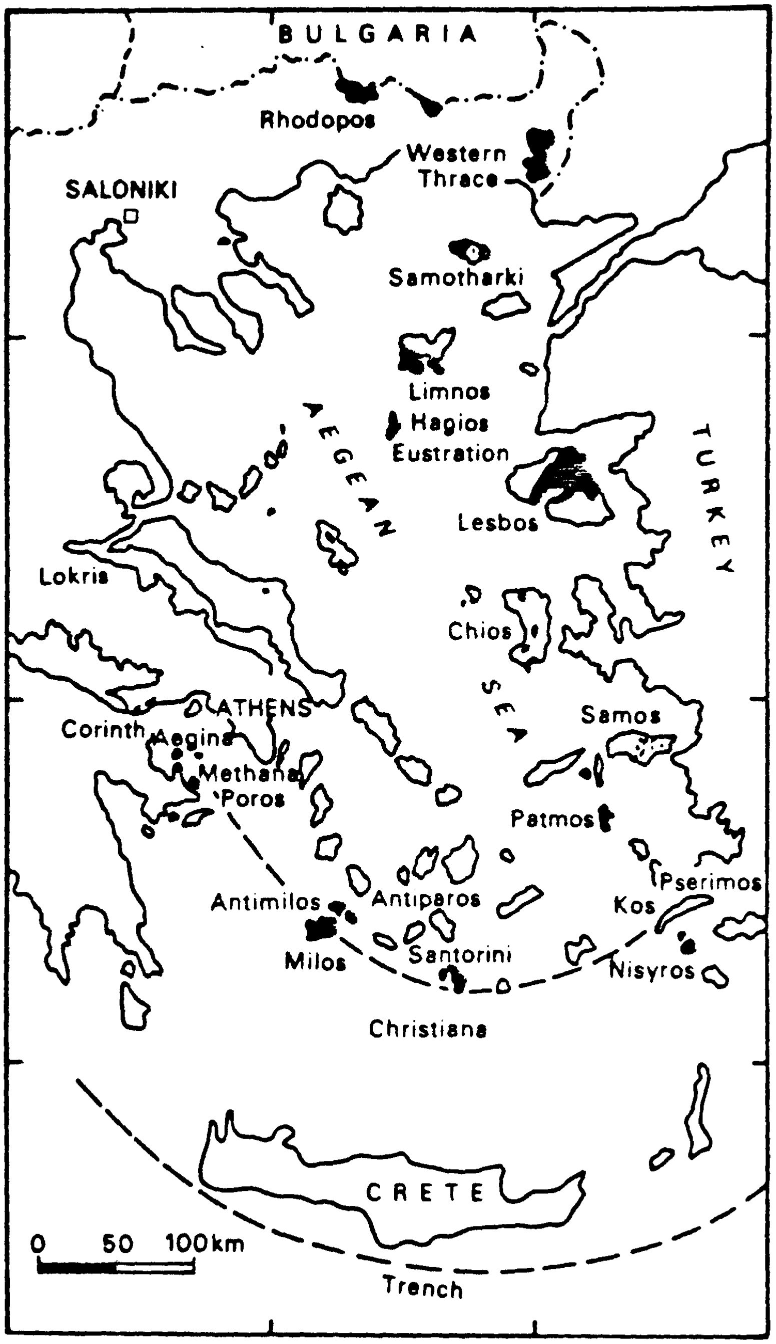


Figure 1. Location Map of the Aegean (Wyers and Barton, 1986).

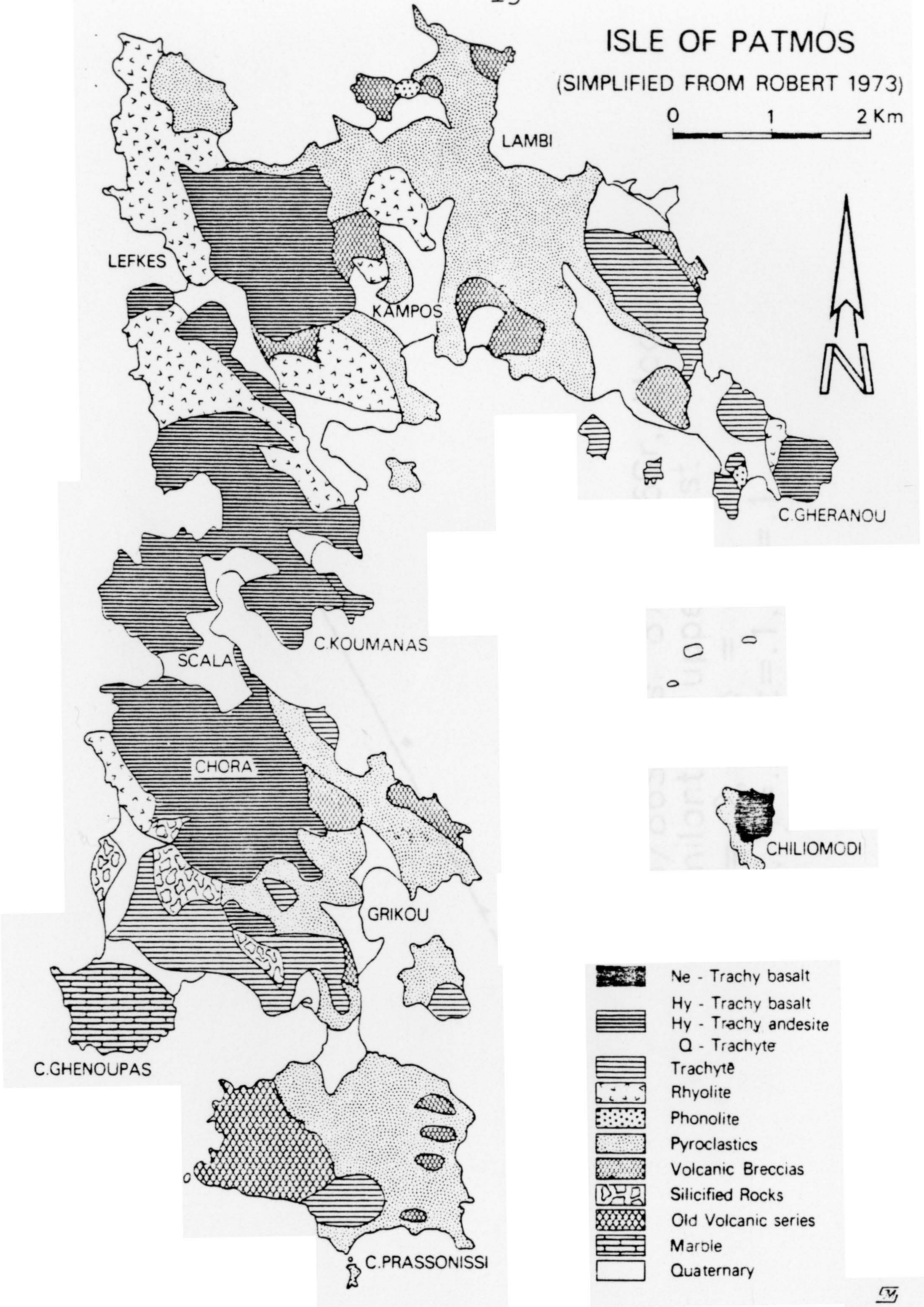


Figure 2. Geologic Map of Patmos
(Wyers and Barton, 1986).

FIGURE 3

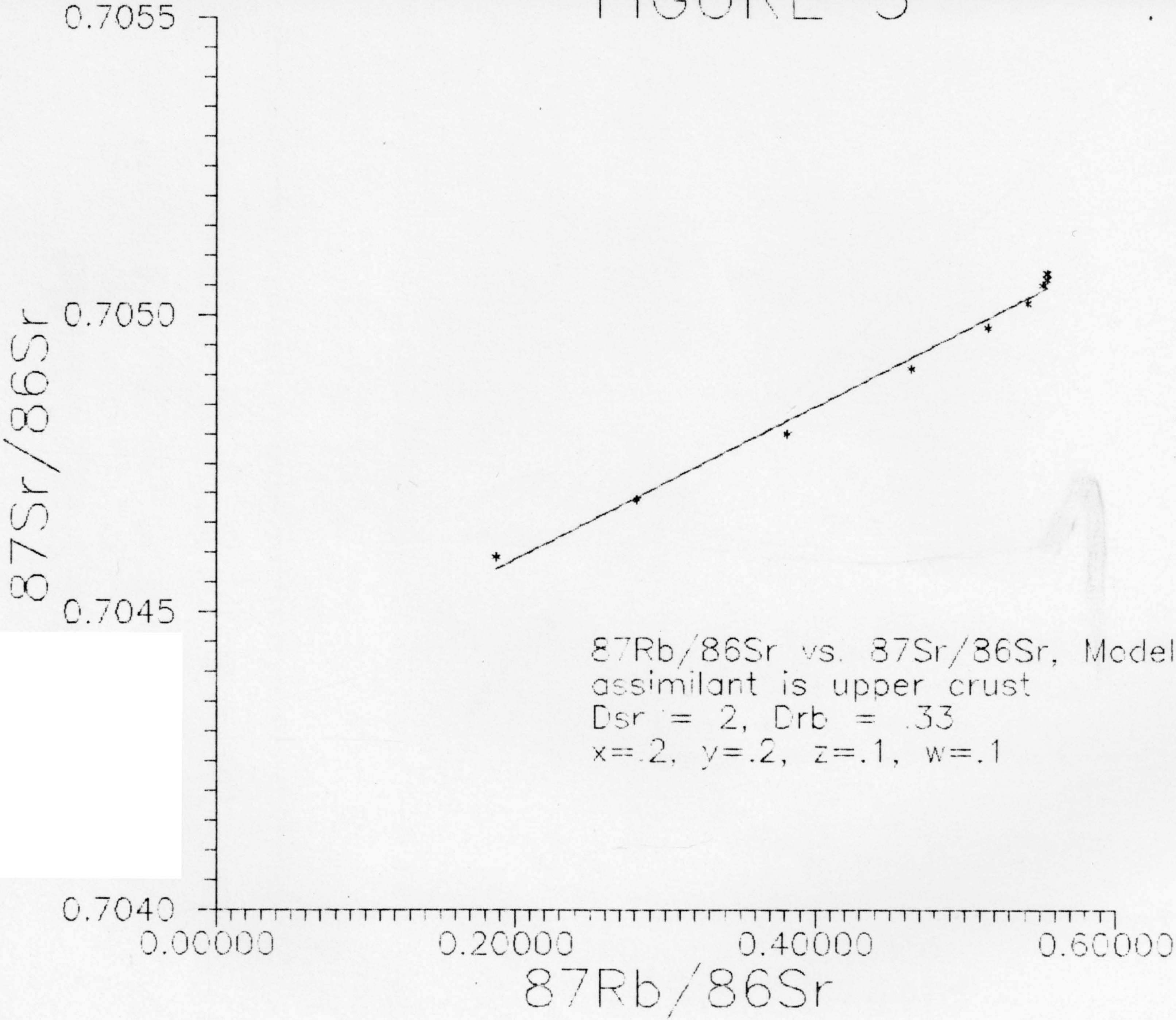
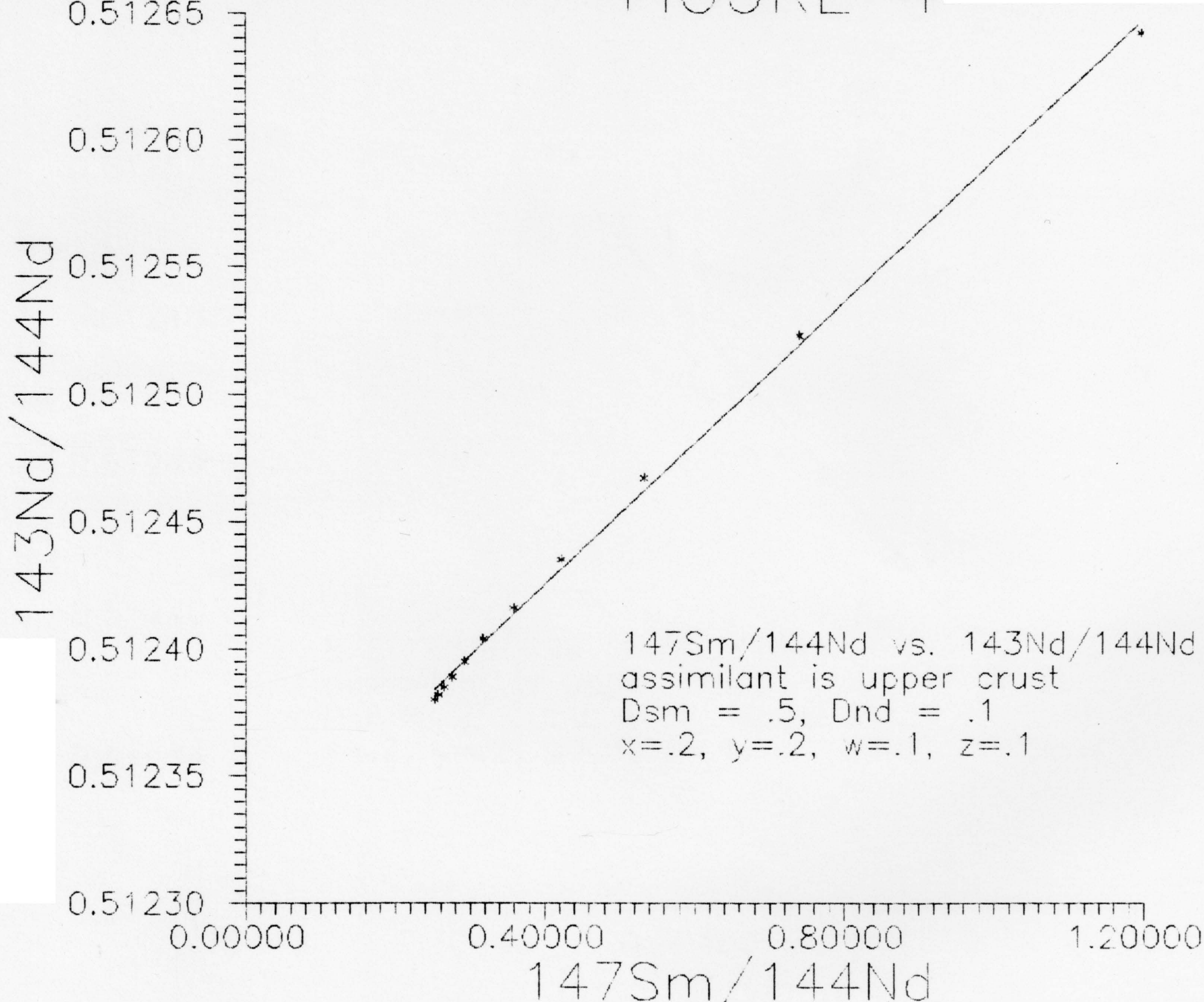

0.7055
0.7050
0.7045
0.7040
87Sr/86Sr
0.00000
0.20000
0.40000
0.60000
87Rb/86Sr
87Rb/86Sr vs. 87Sr/86Sr, Model 1
assimilant is upper crust
Dsr = 2, Drb = .33
x=.2, y=.2, z=.1, w=.1

FIGURE 4



0.51265
0.51260
0.51255
0.51250
0.51245
0.51240
0.51235
0.51230
143Nd/144Nd
0.00000
0.40000
0.80000
1.20000
147Sm/144Nd
147Sm/144Nd vs. 143Nd/144Nd
assimilant is upper crust
Dsm = .5, Dnd = .1
x=.2, y=.2, w=.1, z=.1

FIGURE 5

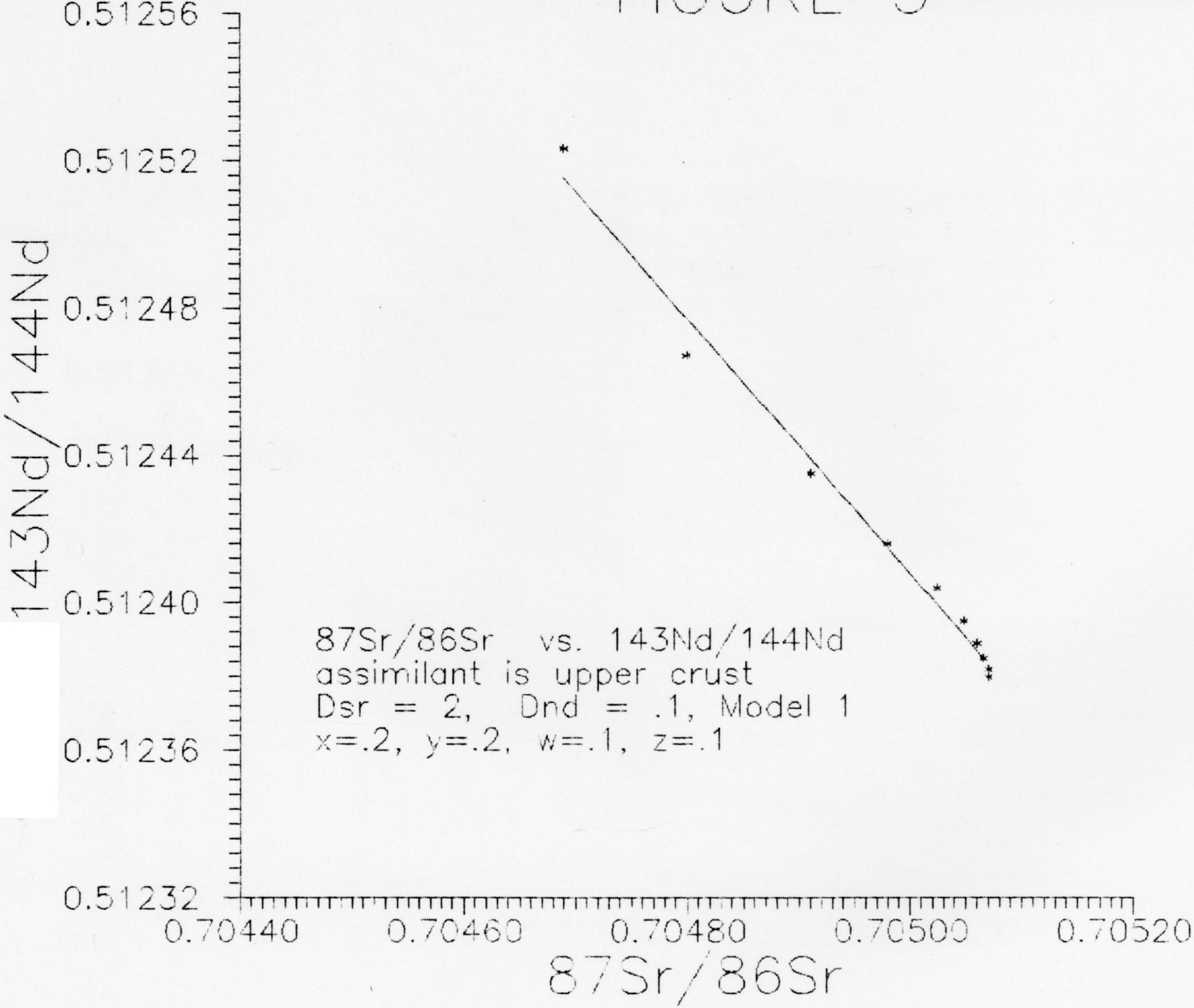

87Sr/86Sr vs. 143Nd/144Nd
assimilant is upper crust
Dsr = 2, Dnd = .1, Model 1
x=.2, y=.2, w=.1, z=.1
0.51256
0.51252
0.51248
0.51244
0.51240
0.51236
0.51232
143Nd/144Nd
0.70440
0.70460
0.70480
0.70500
0.70520
87Sr/86Sr

FIGURE 6

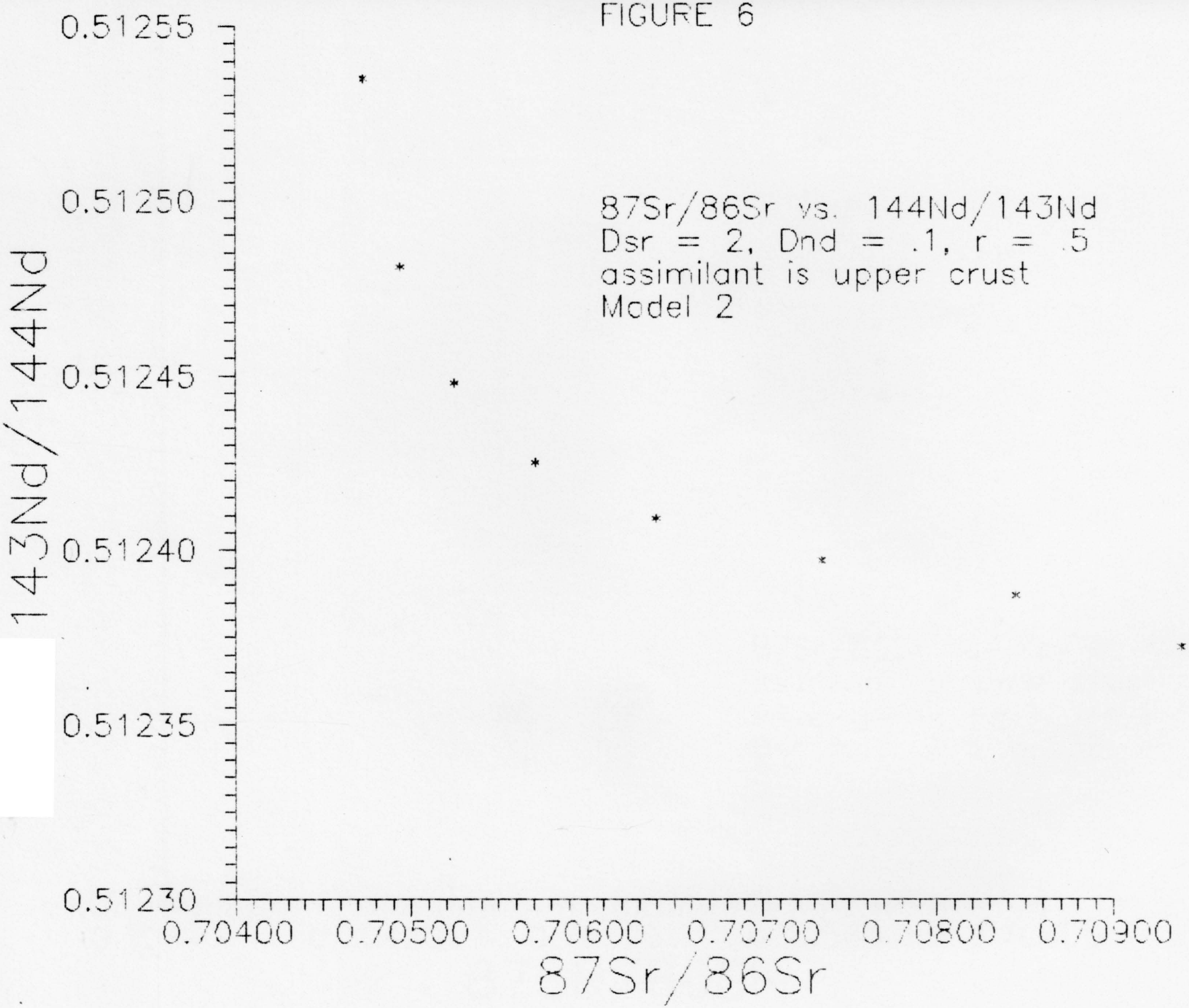
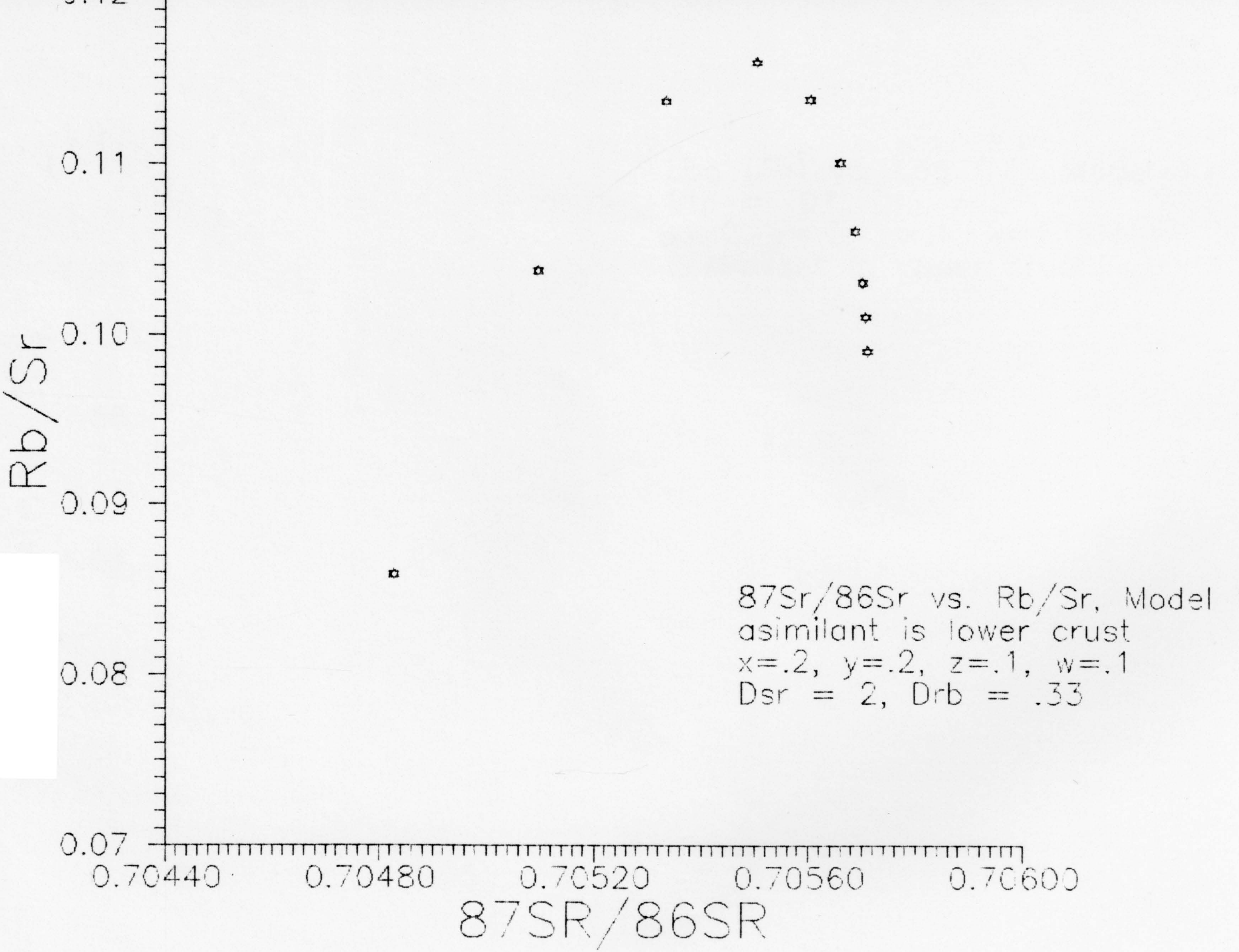

87Sr/86Sr vs. 144Nd/143Nd
Dsr = 2, Dnd = .1, r = .5
assimilant is upper crust
Model 2
0.51255
0.51250
0.51245
0.51240
0.51235
0.51230
143Nd/144Nd
0.70400
0.70500
0.70600
0.70700
0.70800
0.70900
87Sr/86Sr

FIGURE 7


87Sr/86Sr vs. Rb/Sr, Model 1
asimilant is lower crust
x=.2, y=.2, z=.1, w=.1
Dsr = 2, Drb = .33
Rb/Sr
0.12
0.11
0.10
0.09
0.08
0.07
0.70440
0.70480
0.70520
0.70560
0.70600
87SR/86SR

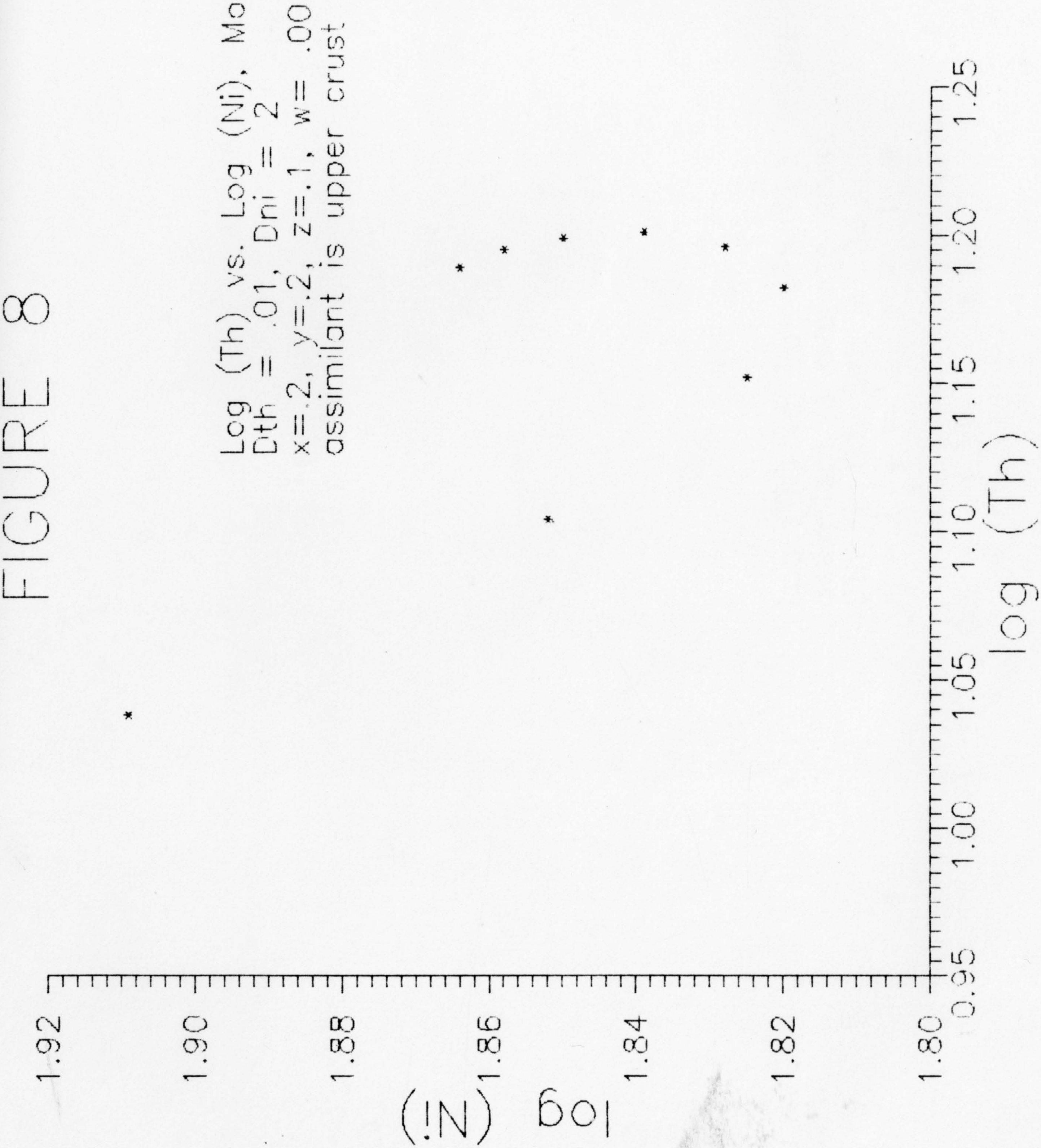


FIGURE 8
Log (Th) vs. Log (Ni), Model 1
Dth = .01, Dni = 2
x=.2, y=.2, z=.1, w= .001
assimilant is upper crust
log (Ni)
1.92
1.90
1.88
1.86
1.84
1.82
1.80
log (Th)
0.95
1.00
1.05
1.10
1.15
1.20
1.25

FIGURE 9

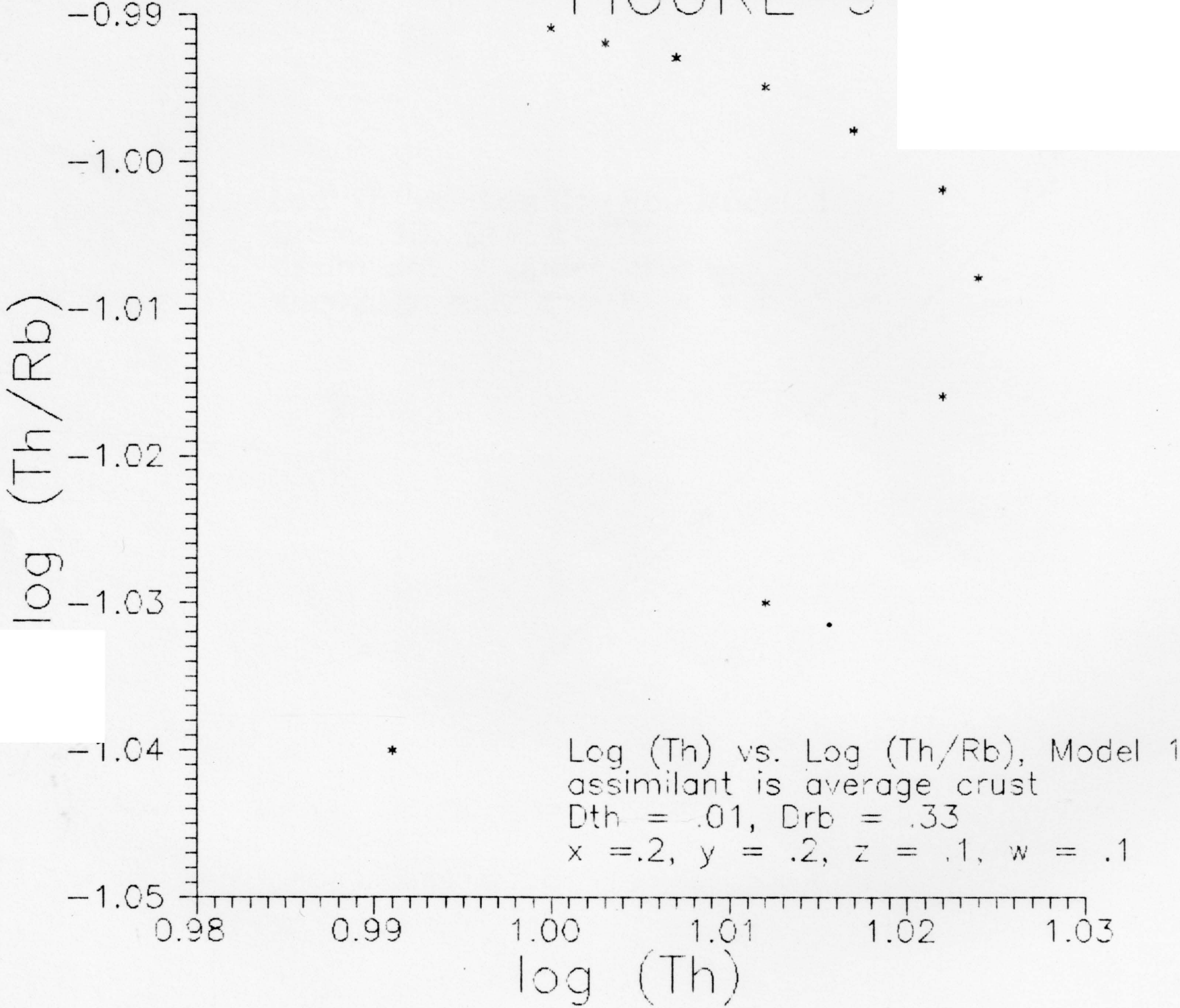

Log (Th) vs. Log (Th/Rb), Model 1
assimilant is average crust
Dth = .01, Drb = .33
x =.2, y = .2, z = .1, w = .1
log (Th/Rb)
−0.99
−1.00
−1.01
−1.02
−1.03
−1.04
−1.05
log (Th)
0.98
0.99
1.00
1.01
1.02
1.03

FIGURE 10.a

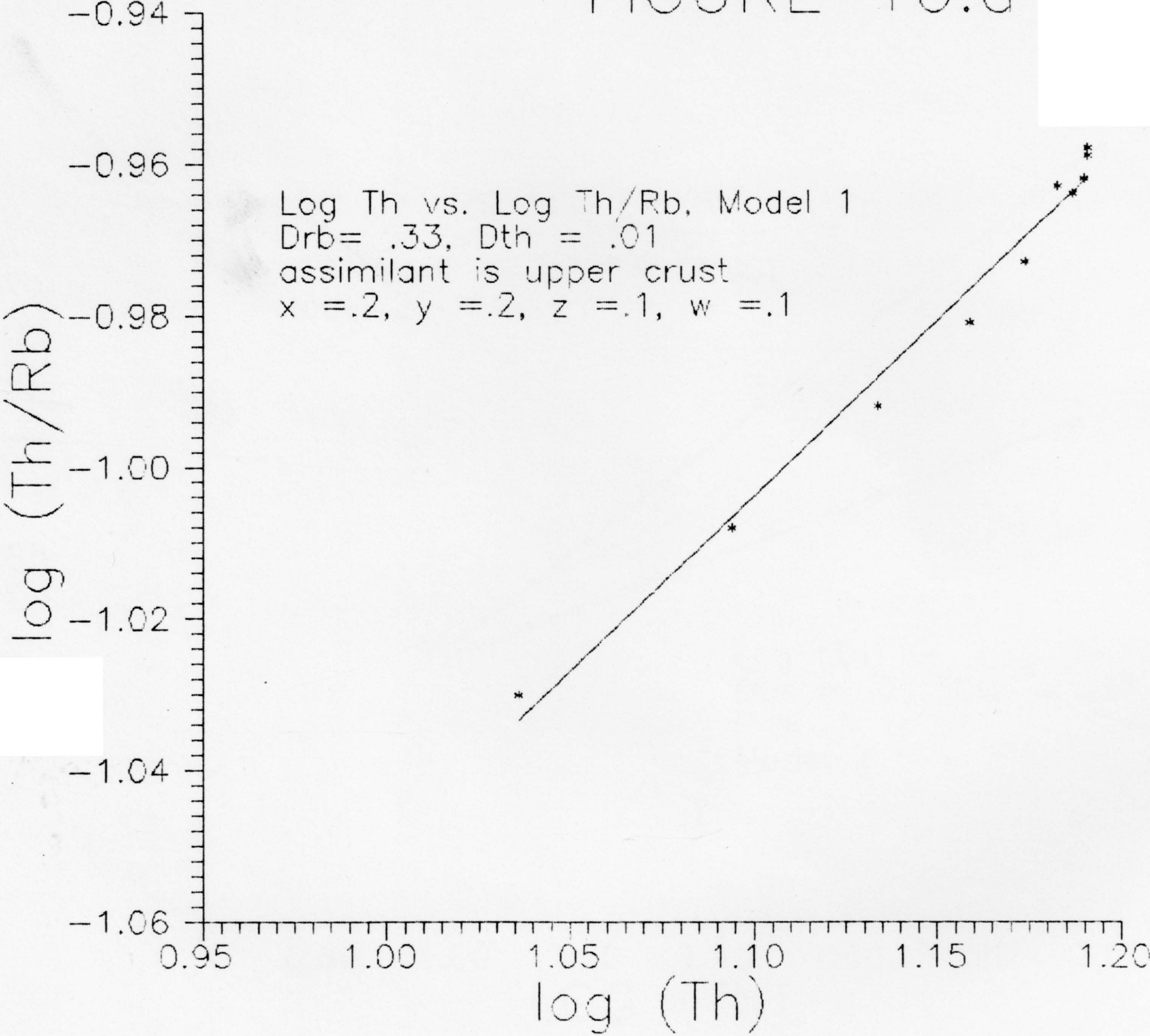
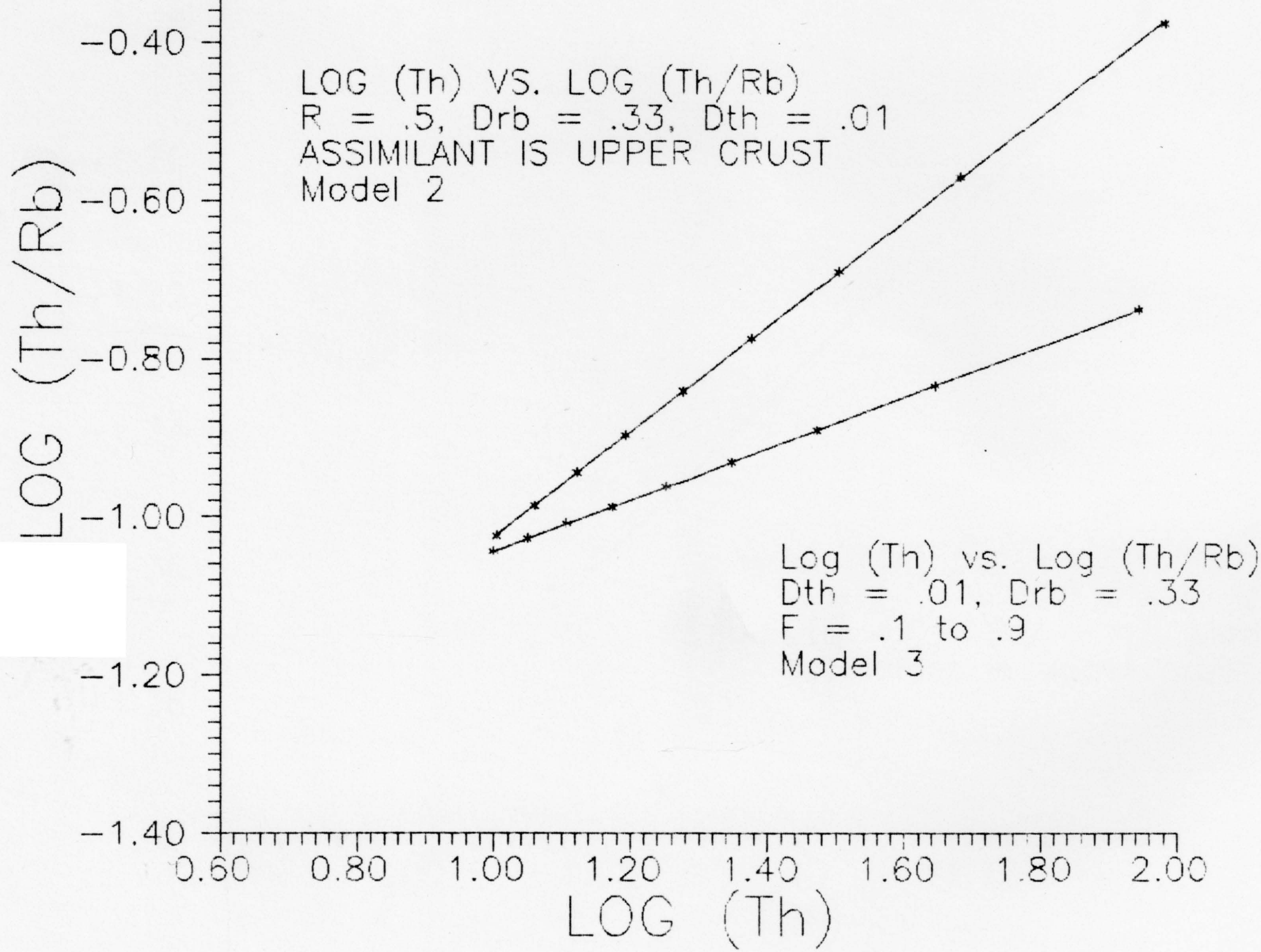

Log Th vs. Log Th/Rb, Model 1
Drb= .33, Dth = .01
assimilant is upper crust
x =.2, y =.2, z =.1, w =.1
log (Th/Rb)
-0.94
-0.96
-0.98
-1.00
-1.02
-1.04
-1.06
log (Th)
0.95
1.00
1.05
1.10
1.15
1.20

FIGURE 10.b



LOG (Th) VS. LOG (Th/Rb)
R = .5, Drb = .33, Dth = .01
ASSIMILANT IS UPPER CRUST
Model 2
Log (Th) vs. Log (Th/Rb)
Dth = .01, Drb = .33
F = .1 to .9
Model 3
-0.20
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
LOG (Th)
LOG (Th/Rb)

FIGURE 11.a

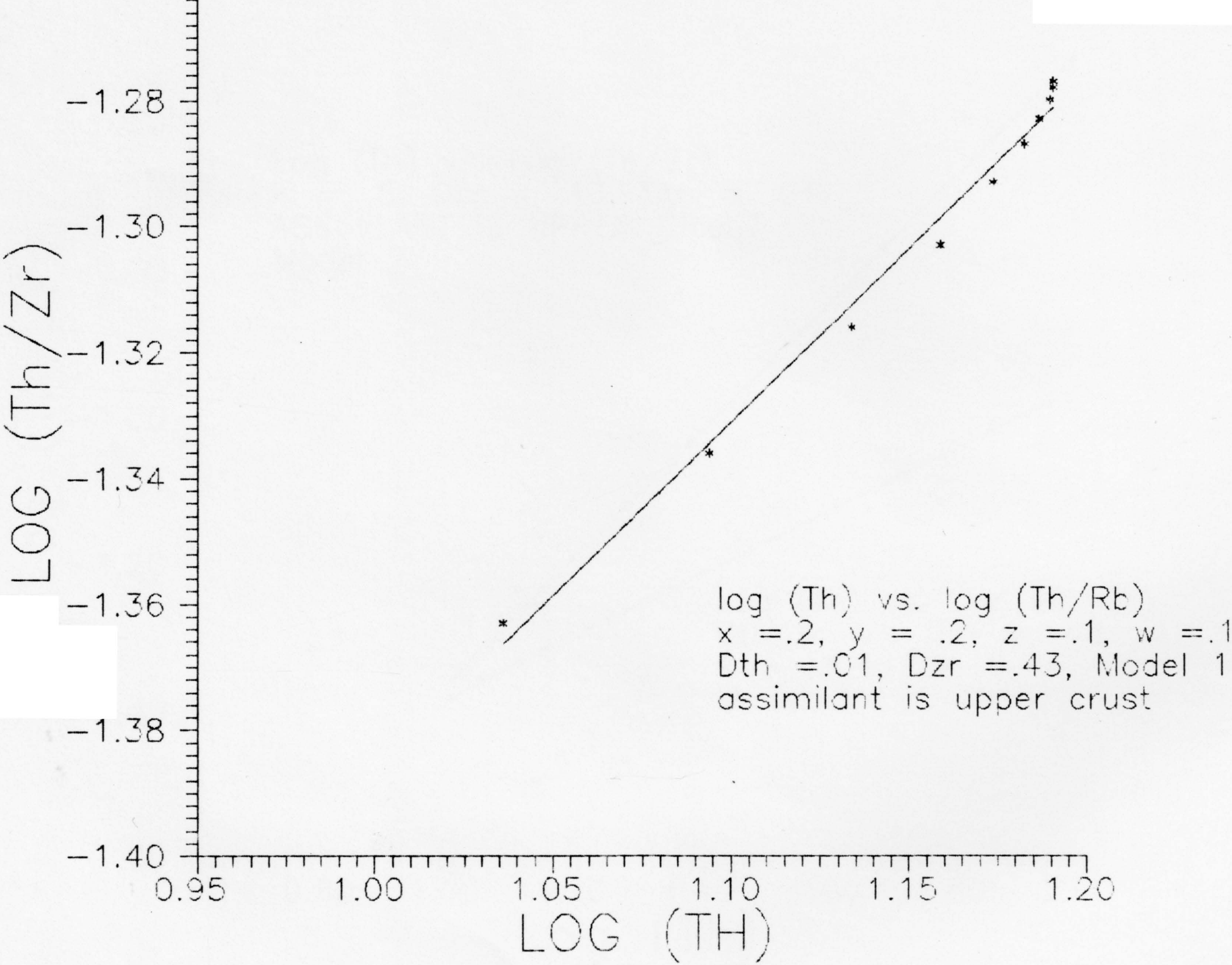
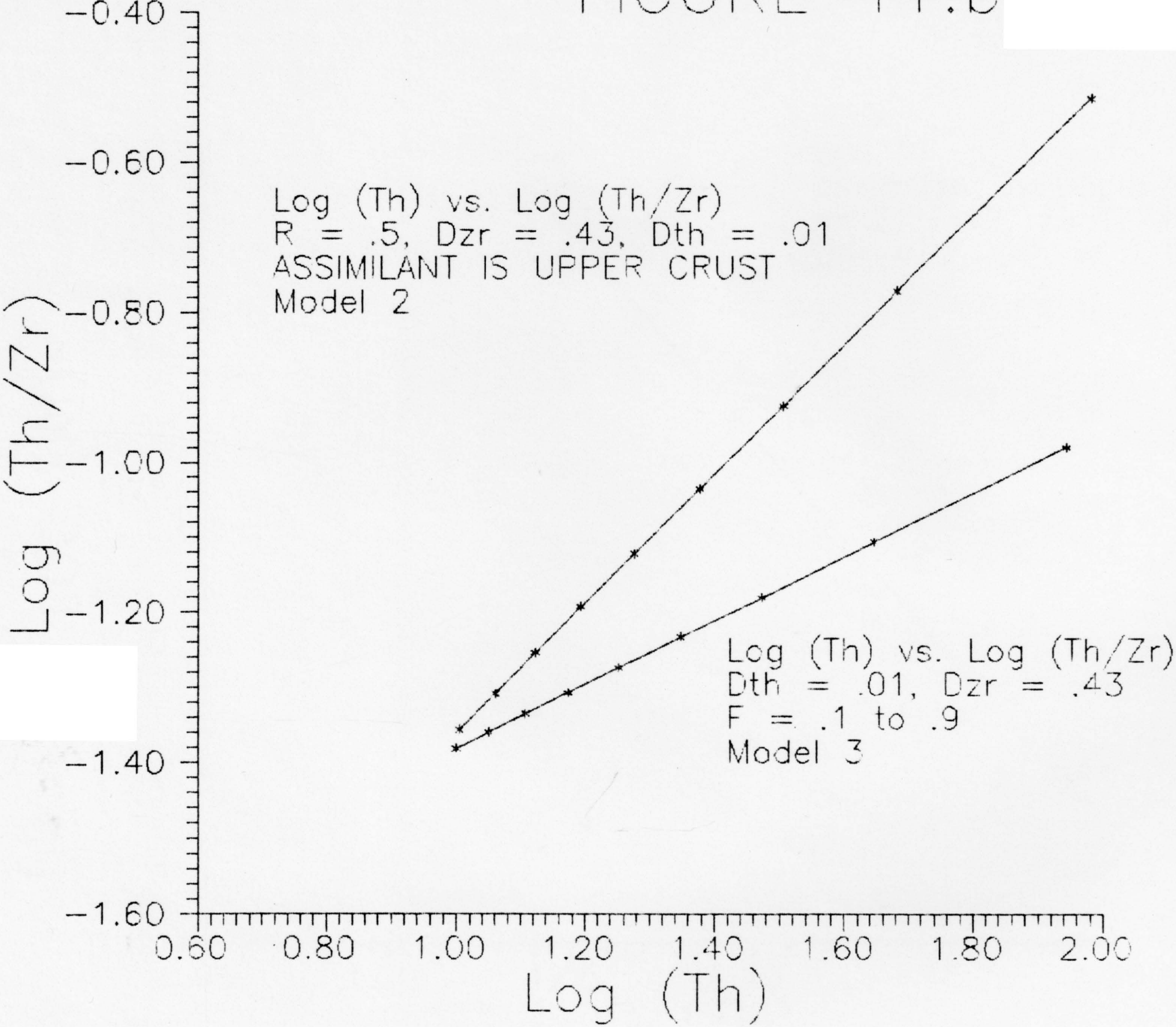

-1.26
-1.28
-1.30
-1.32
-1.34
-1.36
-1.38
-1.40
LOG (Th/Zr)
0.95
1.00
1.05
1.10
1.15
1.20
LOG (TH)
log (Th) vs. log (Th/Rb)
x =.2, y = .2, z =.1, w =.1
Dth =.01, Dzr =.43, Model 1
assimilant is upper crust

FIGURE 11.b



Log (Th) vs. Log (Th/Zr)
R = .5, Dzr = .43, Dth = .01
ASSIMILANT IS UPPER CRUST
Model 2
Log (Th) vs. Log (Th/Zr)
Dth = .01, Dzr = .43
F = .1 to .9
Model 3
-0.40
-0.60
-0.80
-1.00
-1.20
-1.40
-1.60
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
Log (Th)
Log (Th/Zr)

FIGURE 12.a

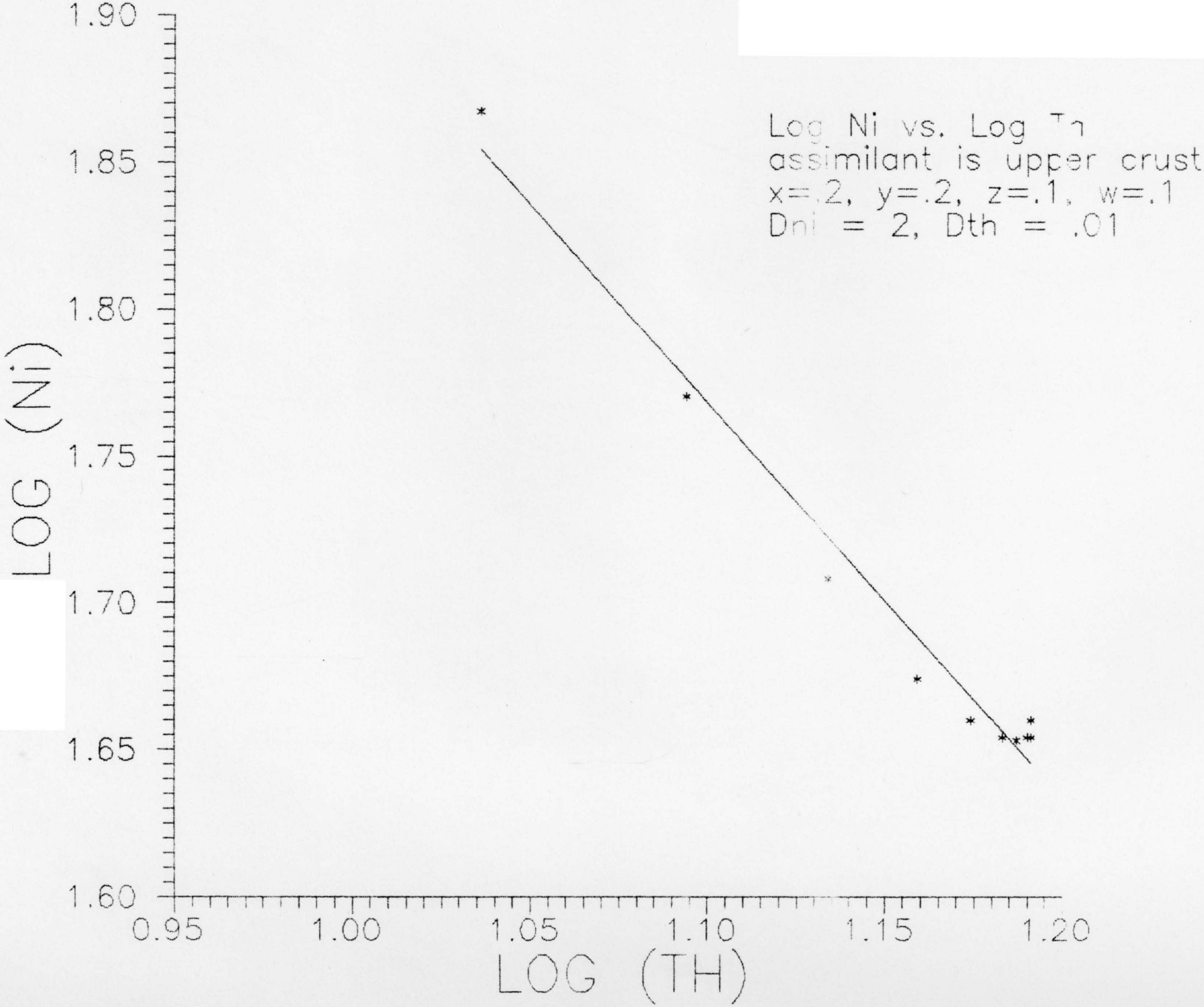
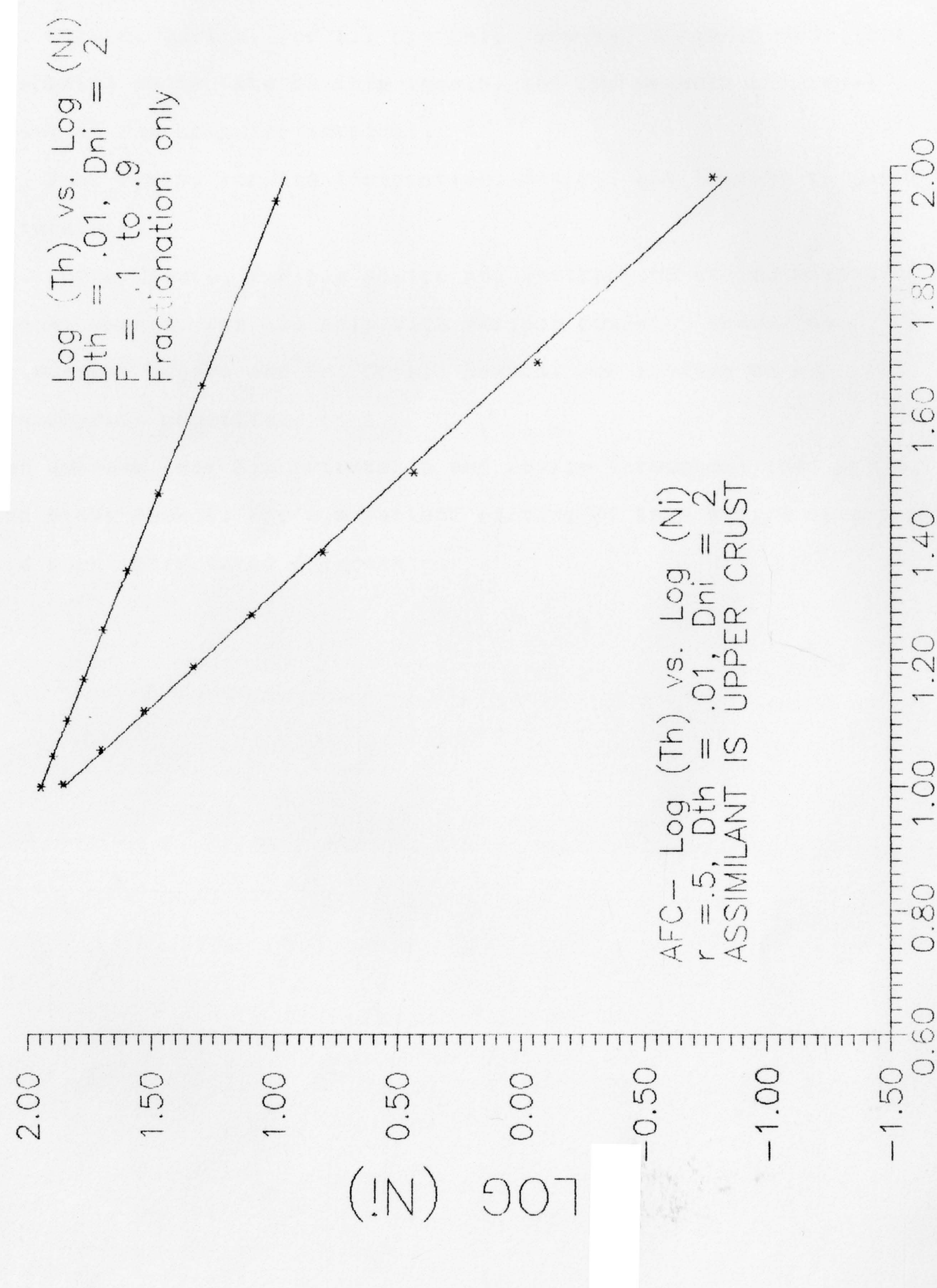

Log Ni vs. Log Th
assimilant is upper crust
x=.2, y=.2, z=.1, w=.1
Dni = 2, Dth = .01
1.90
1.85
1.80
1.75
1.70
1.65
1.60
LOG (Ni)
0.95
1.00
1.05
1.10
1.15
1.20
LOG (TH)

FIGURE 12.b


Log (Th) vs. Log (Ni)
Dth = .01, Dni = 2
F = .1 to .9
Fractionation only
AFC-- Log (Th) vs. Log (Ni)
r = .5, Dth = .01, Dni = 2
ASSIMILANT IS UPPER CRUST
LOG (Th)
LOG (Ni)
0.60
0.80
1.00
1.20
1.40
1.60
1.80
2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
2.00

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Ken Johnson, for his friendship and advice throughout this project.

And Steve Shekut, for his patient editing of this entire thesis and his much appreciated friendship.

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80 PRINT "DEPAOLO (1981) (FRACTIONATION AND ASSIMILATION FOLLOWED BY       "
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100 PRINT "OR O"
110 PRINT "******************************************************************"
120 PRINT
130 PRINT
140 REM
150 REM *** INPUT TRACE ELEMENT DATA ***
160 REM
170 PRINT
180 PRINT "ENTER HEADING FOR INITIAL MAGMA ";
190 INPUT I$
200 PRINT
210 PRINT "ENTER HEADING FOR RECHARGE MAGMA ";
220 INPUT R$
230 PRINT
240 PRINT "ENTER HEADING FOR ASSIMILANT ";
250 INPUT A$
260 PRINT
270 PRINT "ENTER THE SYMBOL FOR THE TRACE ELEMENT ";
280 INPUT TR$
290 PRINT
300 PRINT "ENTER ";TR$;" FOR ";I$;
310 INPUT TT
320 PRINT "ENTER ";TR$;" FOR ";R$;
330 INPUT TR
340 PRINT "ENTER ";TR$;" FOR ";A$;
350 INPUT TA
360 PRINT
370 PRINT "ENTER THE VALUE FOR THE DISTRIBUTION COEFFICIENT ";
380 INPUT D
390 PRINT
400 PRINT "TRACE ELEMENTS (1), OR ISOTOPES (2) ? ";
410 INPUT C
420 PRINT
430 IF C=1 GOTO 590
440 REM
450 REM *** INPUT ISOTOPE DATA ***
460 REM
470 PRINT "ENTER ISOTOPE SYSTEM OF INTEREST ";
480 INPUT IS$
490 PRINT
500 PRINT "ENTER ";IS$;"FOR "I$;
510 INPUT ISO
520 ISOD=ISO
530 PRINT "ENTER ";IS$;"FOR ";R$;
540 INPUT ISR
550 PRINT "ENTER ";IS$;"FOR ";A$;
560 INPUT ISA
570 PRINT
580 REM
Ok
```

```
LIST 580-1160
580 REM
590 REM *** INPUT PHYSICAL PARAMETERS ***
600 REM
610 CLS
620 PRINT "INPUT MA/MC ";
630 INPUT R
640 PRINT "INPUT F (-MASS OF MAGMA IN EACH CYCLE) "
650 PRINT "WHICH IS Mm/Mo IN THE FIRST CYCLE ";
660 INPUT F
670 REM
680 PRINT "INPUT MASS CRYSTALLIZED ";
690 INPUT X
700 PRINT "INPUT MASS ERUPTED ";
710 INPUT Y
720 PRINT "PRINT RECHARGE MASS ";
730 INPUT Z
740 PRINT "INPUT MASS ASSIMILATED ";
750 INPUT W
760 REM
770 REM *** PRINTOUT INPUT DATA ***
780 REM
790 LPRINT "HERE ARE THE INPUT DATA "
800 LPRINT "----------------------- "
810 LPRINT
820 LPRINT "******************************************************************
830 LPRINT
840 LPRINT "INITIAL MAGMA ";
850 LPRINT USING "\           \";I$;
860 LPRINT "  RECHARGE MAGMA ";
870 LPRINT USING "\           \";R$;
880 LPRINT "  ASIMILANT ";
890 LPRINT USING "\           \";A$
900 LPRINT "-----------------------------------------------------------------"
910 LPRINT USING "\  \ ";TR$;
920 LPRINT "  DISTRIBUTION COEFFICIENT - ";
930 LPRINT USING "##.###";D
940 LPRINT USING "####.##                 ";TT;
950 LPRINT USING "####.##                  ";TR;
960 LPRINT USING "####.##";TA
970 IF C=1 THEN GOTO 1020
980 LPRINT USING "\  \";IS$
990 LPRINT USING "#.######                ";ISO;
1000 LPRINT USING "#.######                 ";ISR;
1010 LPRINT USING "#.######";ISA
1020 LPRINT
1030 LPRINT "      O'HARA & MATHEWS METHOD         DEPAOLO METHOD"
1040 LPRINT
1050 LPRINT "                    TR ELEMENT  ISOTOPE  TR ELEMENT ISOTOPE"
1060 CLS
1070 PRINT "ENTER NUMBER OF MIXING CYCLES ";
1080 INPUT N
1090 REM
1100 REM *** CALAULATE NEW ABUNDANCES ***
1110 REM
1120 NI=1
1130 CO=TT
1140 DO=TT
1150 MO=1
1160 MI=MO
Ok
```

```
LIST 1160-1710
1160 MI=MO
1170 MNI=MO
1180 IF C=1 GOTO 1300
1190 IO=TT/(ISO+1)
1200 I1O=TT-IO
1210 IOD=IO
1220 I1OD=I1O
1230 IR=TR/(ISR+1)
1240 I1R=TR-IR
1250 IA=TA/(ISA+1)
1260 I1A=TA-IA
1270 REM
1280 REM *** O'HARA & MATTHEWS METHOD ***
1290 REM
1300 CI=CO*((1-X)^(D-1))
1310 MN=MI*(1-X-Y)+Z+W
1320 CN=(CI*MI*(1-X-Y))/MN+(Z*TR)/MN+(W*TA)/MN
1330 REM
1340 REM *** DEPAOLO METHOD ***
1350 REM
1360 A=(R+D-1)/(R-1)
1370 CJ=DO*((F^-A)+(R/(R-1))*(TA/(A*DO))*(1-F^-A))
1380 MND=MNI*(F-Y)+Z
1390 CM=CJ*MNI*(F-Y)/MND+(Z*TR)/MND
1400 IF C=1 GOTO 1600
1410 REM
1420 REM *** CALCULATE ISOTOPE RATIOS ***
1430 REM
1440 REM
1450 IOI=IO*((1-X)^(D-1))
1460 CNIO=(IOI*MI*(1-X-Y))/MN+(Z*IR)/MN+(W*IA)/MN
1470 I1OI=I1O*((1-X)^(D-1))
1480 CNI1O=(I1OI*MI*(1-X-Y))/MN+(Z*I1R)/MN+(W*I1A)/MN
1490 CJIO=IOD*((F^-A)+(R/(R-1))*(IA/(A*IOD))*(1-F^-A))
1500 CJI1O=I1OD*((F^-A)+(R/(R-1))*(I1A/(A*I1OD))*(1-F^-A))
1510 CMIO=CJIO*MNI*(F-Y)/MND+(Z*IR)/MND
1520 CMI1O=CJI1O*MNI*(F-Y)/MND+(Z*I1R)/MND
1530 REM
1540 REM *** CALCULATE ISOTOPE RATIOS ***
1550 REM
1560 RATIO1=CNI1O/CNIO
1570 RATIO2=CMI1O/CMIO
1580 REM
1590 REM *** PRINT RESULTS ***
1600 LPRINT "CYCLE ";
1610 LPRINT USING "##";NI
1620 LPRINT "MASS = ";
1630 LPRINT USING "#.##    ";MN;
1640 LPRINT USING "####.##      ";CN;
1650 IF C=1 GOTO 1690
1660 LPRINT USING "#.#######  ";RATIO1;
1670 LPRINT "MASS = ";
1680 LPRINT USING "#.##  ";MND;
1690 LPRINT USING "####.##      ";CM;
1700 IF C=1 GOTO 1720
1710 LPRINT USING "#.#######  ";RATIO2
Ok
```

```
LIST 1720-1970
1720 IF NI=N GOTO 1850
1730 NI=NI+1
1740 CO=CN
1750 DO=CM
1760 MI=MN
1770 MNI=MND
1780 IF C=1 GOTO 1300
1790 IO=CNIO
1800 I1O=CNI1O
1810 IOD=CMIO
1820 I1OD=CMI1O
1830 GOTO 1300
1840 REM
1850 REM *** CHANGE INPUT ***
1860 REM
1870 CLS
1880 PRINT "DO YOU WISH TO CHANGE THE INPUT DATA (Y/N) ?";
1890 INPUT Q$
1900 IF Q$="N" THEN GOTO 1970
1910 PRINT
1920 PRINT "ALL DATA OR ONLY THE PHYSICAL PARAMETERS (Y/N) ?;
1930 INPUT Q$
1940 IF Q$="Y" THEN GOTO 150 ELSE GOTO 590
1950 PRINT
1960 PRINT
1970 END
Ok
```

```
LIST
10 PRINT"**********************************************************************
**"
20 PRINT"THIS PROGRAM CALCULATES TRACE ELEMENT VARIATIONS DURING COMBINED FRAC
"
30 PRINT"IONATION AND ASSIMILATION "
40 PRINT"**********************************************************************
**"
50 REM
60 REM
70 PRINT
80 PRINT
90 PRINT "ENTER THE SYMBOL FOR THE TRACE ELEMENT ";
100 INPUT T$
110 PRINT
120 PRINT "ENTER INITIAL CONCENTRATION FOR IN THE MAGMA ";T$
130 INPUT CO
140 PRINT
150 PRINT "ENTER THE VALUE FOR D ";
160 INPUT D
170 PRINT
180 PRINT "ENTER THE CONCENTRATION OF ";T$";IN THE COUNTRY ROCK"
190 INPUT CS
200 PRINT
210 PRINT "ENTER MASS ASSIMILATED/MASS CRYSTALLIZED ";
220 INPUT R
230 IF R<1 THEN F=.9
240 IF R>1 THEN F=1.1
250 PRINT
260 LPRINT "*************************************************************"
270 LPRINT "CO= "; CO;" D= ";D;" MA/MC= ";R
280 LPRINT
290 Z=(R+D-1)/(R-1)
300 CM=CO*(F^(-Z))+(R*CS*(1-F^(-Z)))/(Z*(R-1)*CO)
310 LPRINT "F=";F
320 LPRINT "  CONCENTRATION =";CM
330 LPRINT
340 IF F<=.1 THEN GOTO 410
350 IF F>=2! THEN GOTO 410
360 IF R<1 THEN F=F-.1
370 IF R>1 THEN GOTO 390
380 GOTO 400
390 F=F+.1
400 GOTO 290
410 END
Ok
```

```
LOAD"tiffabny
Ok
LIST
10 PRINT"***********************************************************************
**"
20 PRINT"THIS PROGRAM CALCULATES TRACE ELEMENT VARIATIONS DURING RAYLEIGH FRACT
"
30 PRINT"IONATION "
40 PRINT"***********************************************************************
**"
50 REM
60 REM
70 PRINT
80 PRINT
90 PRINT "ENTER THE SYMBOL FOR THE TRACE ELEMENT ";
100 INPUT T$
110 PRINT
120 PRINT "ENTER INITIAL CONCENTRATION FOR ";T$
130 INPUT CO
140 PRINT
150 PRINT "ENTER THE VALUE FOR D ";
160 INPUT D
170 PRINT
180 LPRINT"****************************************************************"
190 F=.9
200 CI=CO*F^(D-1)
210 LPRINT "CO= "; CO
220 LPRINT
230 LPRINT "F= "; F;
240 LPRINT "                         CI= "; CI
250 F=F-.1
260 IF F=0 THEN GOTO 280
270 GOTO 200
280 END
Ok
```

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